Renewable and Sustainable Energy Reviews 15 (2011) 4187–4199

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A comprehensive techno-economical review of indirect solar desalination

Muhammad Tauha Ali*, Hassan E.S. Fath, Peter R. Armstrong

Masdar Institute of Science and Technology, Abu Dhabi 54224, United Arab Emirates

ARTICLE INFO

Article history:
Received 3 February 2011
Accepted 30 May 2011
Available online 17 September 2011

Keywords:
Solar desalination
Solar energy
Desalination economics
Solar desalination plants
Desalination technologies

ABSTRACT

Solar powered desalination has been the focus of great interest recently worldwide. In the past, majority of the experimental investigations focused on solar coupled thermally driven conventional desalination technologies such as Multi-Stage Flash (MSF) and Multi-Effect Distillation (MED). With the advancement in membrane technology and its advantages such as high Recovery Ratios (RR) and low specific energy requirements Reverse Osmosis (RO) desalination has gained popularity. Currently, 52% of the indirect solar desalination plants are RO based with MED and MSF having a 13% and 9% share respectively. Membrane Distillation (MD) based plants represent 16% of the total and have been a focus of recent research efforts. This paper aims to provide a comprehensive review of all the indirect solar desalination technologies along with plant specific technical details. Efforts assessing the economic feasibility and cost affecting parameters for each desalination technology are also reviewed.

Contents

1. Introduction

Water is essential for life. Around 97.5% of earth's water is salt water while only 2.5% is fresh water that can be used by humans. It is the basis for social well-being of people. As populations continue to grow, scarcity of fresh water sources has driven technological advances in desalination of brackish water and sea water for meeting social and economic needs for potable water.

There are many methods of desalination which can be classified into membrane methods and distillation methods. Among membrane desalination methods such as Reverse Osmosis (RO) and Membrane Distillation (MD), RO is the proven membrane desalination method. Multi-Stage Flash (MSF) and Multi-Effect Distillation (MED) are the two conventional distillation methods being used in solar driven desalination technologies. In the recent years, through several breakthroughs in membrane research, membrane methods are gaining popularity over other distillation methods. After 2000, a 9% annual growth is observed in RO based membrane-based desalination plants while only 5% annual growth is observed for MSF based distillation plants [1].

These methods require thermal and/or electrical energy. In the recent years, much attention has been paid to renewable energy for their environmentally friendly nature over fossil fuels. The abundance of solar resource in water-starved countries coupled with

* Corresponding author. Tel.: +971 2 810 9151; fax: +971 2 810 9221.
E-mail address: mali@masdar.ac.ae (M.T. Ali).

1364-0321/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.rser.2011.05.012

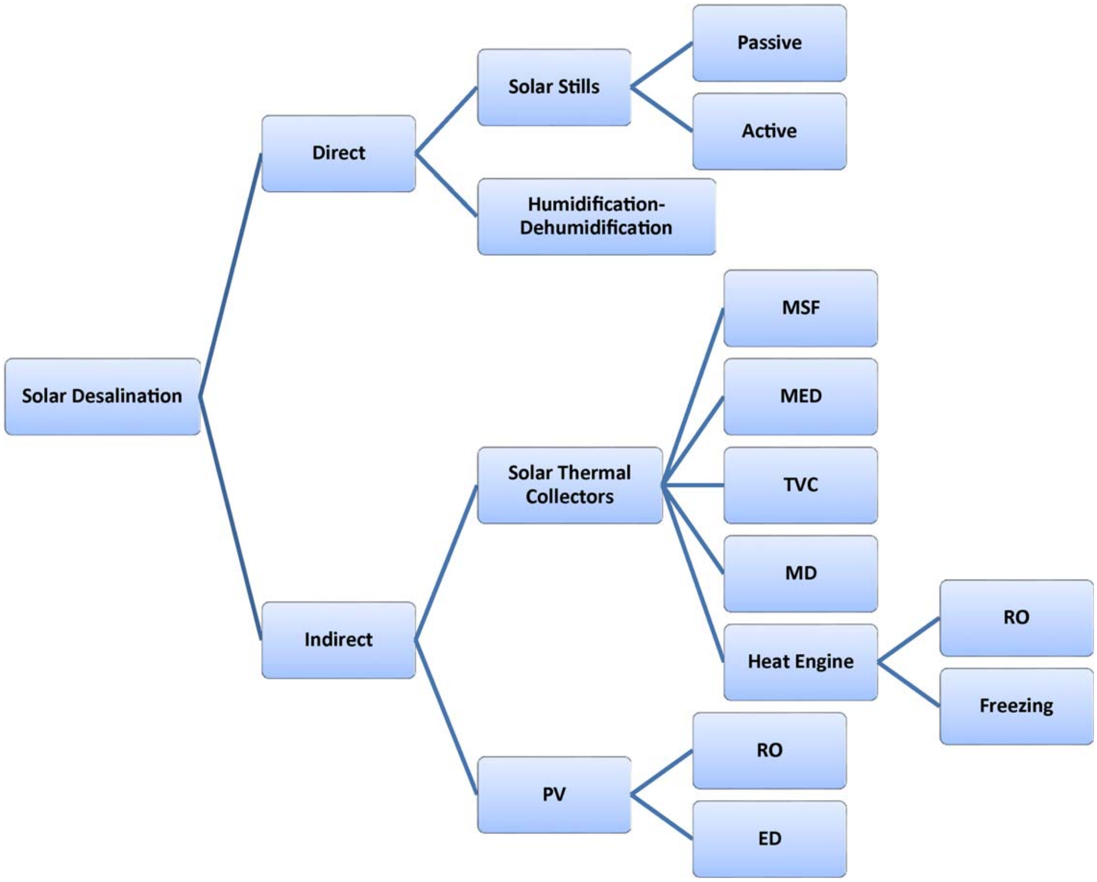

Fig. 1. Pilot tested solar desalination technologies.

a seasonal match in water demand and solar resource appears to be a good source of environmentally-friendly energy for desalination. Solar energy can be harvested directly in the form of electrical energy through photo-voltaic (PV) modules or through solar thermal collectors. Desalination using solar energy through PV modules or solar collectors is referred to as indirect solar desalination. Fig. 1 presents different methods of solar desalination that have been investigated on a lab or commercial scale.

This paper presents a comprehensive survey and review of the efforts made in solar desalination with focus on indirect solar desalination.

2. Literature review

Application of solar energy for desalination dates back to fourth century B.C. However, the first documented work is attributed to Arab chemists using solar distillation for making perfume in the 16th century [2]. This section presents a brief review of literature present for solar desalination technologies such as solar stills, humidification-dehumidification desalination and indirect solar desalination.

2.1. Solar Stills

Solar energy can be directly used in solar stills and humidification and dehumidification desalination to obtain distilled water. Solar stills mimic the natural hydrological cycle. Salty water is collected in an air-tight basin made of concrete, galvanized iron sheet or fiber reinforced plastic [3]. The basin is blackened to increase absorption of solar energy. Water evaporates due to heating and gets condensed on the glass or plastic cover. The condensed water is then collected at the lower end of the cover. Solar stills are classified into passive and active stills based on their heating principle [4]: Single-slope Solar Still with Passive Condenser, Double Condensing Chamber Solar Still, Vertical Solar Still, Conical Solar Still, Inverted Absorber Solar Still, Multi-Wick Solar Still and Multiple Effect Solar Still are some of types of passive solar stills. In active solar stills, solar energy is fed indirectly by means of non-concentrating or concentrating solar collectors for heating the water. A detailed review on active solar distillation is provided in [5]. A comprehensive review of types of solar stills and efforts made is presented in [3,4,6–8]. The effects of different parameters such as water-glass temperature difference, glass angle, depth of water etc. on solar still performance are provided in [9]. In [10] estimates of water costs from these solar stills are provided.

2.2. Humidification–Dehumidification desalination

In Humidification–Dehumidification (HD) desalination concept, dry hot air is passed over salty water for humidification. This humid air is then condensed over a cool surface to obtain water. Applications of this concept are collection of morning dew by people of Sahara desert [11] and collection of condensed water from the cooling coils of air conditioning units [12]. Adsorption–desorption and Absorption–desorption methods use the principle of HD in which moisture in the humid air is adsorbed/absorbed by an adsorbing/absorbing material such as silica gel/LiBr which is then regenerated by heating [13–15]. A review of different HD methods is presented in [16,17]. Details on the demonstration of a solar driven HD plant in 2005 in Jeddah, Saudi Arabia is provided in [18] along with economic comparison of the solar HD technique with a PV powered RO plant. It is suggested that for small scale

applications HD desalination should be considered due to its operational simplicity as compared to PV-RO plants with similar energy cost. A comprehensive review on water cost and economics of HD based desalination is provided in [19].

2.3. Indirect solar desalination

The majority of large scale applications of solar desalination use solar energy indirectly. In these systems, solar energy is harvested by using non-concentrating or concentrating solar thermal collectors or photo-voltaic panels. A comprehensive review of these collectors is provided in [20]. The collected energy is used to drive thermal desalination processes such as MSF, MED, Thermal Vapor Compression (TVC) or MD or in membrane desalination methods such as RO and Electrodialysis (ED). In [21], a review of efforts made for linking renewable energies with desalination technologies up till 1981 is given. A review of efforts focused to solar desalination is given in [22] and cover developments up to 1987. In [23–30], a general discussion of efforts made for using renewable energy sources such as solar, wind, geothermal and wave for desalination is presented. In [31–33] focus has been given to solar powered rankine cycle for RO. Experimental investigations and proposals assessing different scenarios for powering RO desalination by rankine cycle are presented. A review of efforts focused towards renewable powered membrane desalination is presented in [34–37]. Membrane distillation driven by renewable energy is the focus in [38–40]. Finally a comparison between membrane and thermal desalination driven by solar technologies is presented in [41]. The aim of this paper is to update and present efforts in indirect solar powered desalination and recommend feasible solar powered desalination technologies based on these efforts.

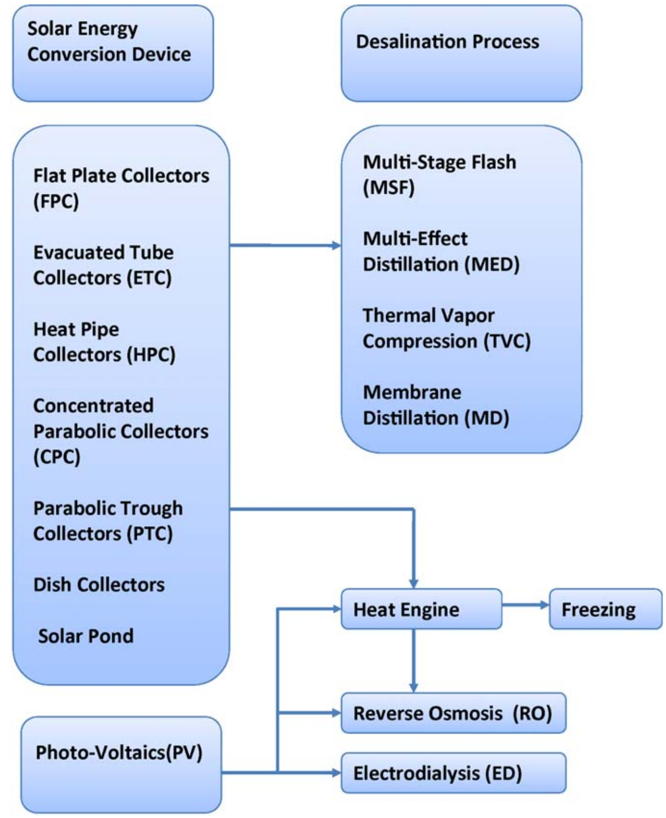

Fig. 2. Indirect solar desalination technologies with possible solar energy conversion device.

3. Solar driven desalination technologies

Indirect solar powered desalination systems can be classified into thermal, mechanical or electric driven technologies. MSF, MED, TVC and MD are thermal desalination technologies that require solar thermal collectors as their energy source while RO and Freezing are mechanical driven technologies. ED is the only solar desalination technology that requires electricity although RO and Freezing may also be electrically powered. Fig. 2 presents possible solar energy conversion devices that can be linked with indirect solar desalination technologies.

3.1. Multi-Stage Flash (MSF)

MSF is the most commonly used thermal technology used in gulf using fossil fuels. The world's largest desalination plants are based on this technology. In MSF, water is heated by the waste heat in brine heater and then flashed in different chambers by varying saturation pressure. For coupling with solar energy, a way of regulating top brine temperature (TBT) is necessary to avoid unstable operation of the plant. In Safat, Kuwait a self regulating solar MSF system was installed in 1983. The system consisted of a hot water thermal storage with a three-way valve for maintaining a constant collector field output temperature [42]. The specific energy consumption (SEC) of the plant was reported to be in the range of 81–106 kWh/m^3 for a water temperature difference between hot brine and inlet sea water of 10–45 °C. The Gain Output Ratio (GOR) was in the range of 6.5–8 which is typical of a MSF plant with Recovery Ratio (RR) of 6%.

Another MSF system was installed at El Paso, USA for investigation of feasibility of using solar ponds for desalination [43]. A multi-effect multi-stage (MEMS) system was installed in 1987 along with a falling film MED unit. The MEMS unit is a three effect, four stage MSF unit. The advantages of this system are that it can use low grade heat and use jet pumps (eductors) to produce vacuum. Jet pumps convert pressure head of the stream into velocity head in the suction chamber and have no moving parts.

Atlantis "Autoflash" is another type of MSF system designed to be coupled with a heat source of varying temperature [44]. In the "Autoflash" process water is sucked through a de-aerator, preheated in condenser tubes by vapor releasing heat of condensation at sub-atmospheric pressures. As, the system is designed to operate with a heat source with varying temperatures, it employs a proprietary passive inter-stage pressure regulation system so that it can operate from a heat source with varying temperature without using any mechanical or electronic control devices. The system can operate at TBT range of 30–95 °C.

A recent low-TBT MSF system was tested in Egypt [45]. The system successfully operated with TBT range of 40–60 °C producing 4.2–7 kg/d/m^2 of collector area in summer 2005. This single stage system is powered by flat plate collectors and can be used to supply water in rural areas without technical expertise.

The capital cost components for a standalone solar powered MSF plant are mainly the capital cost of solar collectors, PV arrays, battery storage, thermal storage or fossil fuel powered generator, desalination unit and steam generator. Operating costs include chemical cost, maintenance cost and personnel cost which are less than 20% of total cost [46]. Cost of water obtained from solar-MSF plants are in the range of 1–5$/m^3 [46,47]. In [48], an economic comparison between solar-MSF with fossil fuel backup and a fossil fuel driven MSF plant is given. The main parameters affecting water cost are suggested to be the Performance Ratio (PR) and solar fraction of the plant similar to the situation in solar cooling as noted by [49]. Solar fraction represents the energy needs of the plant supplied by the collector field while PR is the amount of water produced in pounds to 1000Btu of thermal energy input [43]. It is estimated

Table 1
Solar-MSF desalination plants.

Location	Year	Energy source	Feed water type	Energy source details	Capacity (m^3/d)	SEC (kWh/m^3)	Specific plant details
La Paz, Mexico [50]	1980	PTC-FPC	Seawater	194 m^2 FPC, 160 m^2 PTC with two-axis tracking	10	<144	10 stage
Las Barranas, Mexico [51]	1980	PTC-HPC	Seawater	550.8 m^2 PTC, 1540 m^2 HPC, 16 m^3 hot oil storage, 114 m^3 hot water storage	20		
Gran Canary, Spain [52]	1981	Low Concentration Solar Collectors	Seawater		10		
Safat, Kuwait [42]	1983	PTC	Seawater	220 m^2 PTC, 7 m^3 hot water storage	10	81–106	12 stages, GOR 6.5–8, RR 6%, 10 times output of solar still of same collection area
El Paso, USA [43]	1987	Solar Pond	Seawater	3000 m^2 with 3.75 m depth	2.35–7.2		Multi-effect Multi-Stage Spin Flash (MEMS), Brine Concentrate Recovery System (BCRS) for testing Zero Discharge Concept, PR 1.7–3.3
Gaza, Palestine [53]	1999	FPC-PV	Brackish Water	5.1 m^2 FPC, PV with battery storage	0.2		4 stage MSF, thermo-siphoning from FPC, experimental, batch process, PV for vacuum pump and controls
Berken, Germany [54]		Solar Collectors	Seawater		10		
Lempedusa Island, Italy [23]		Solar collectors			0.3		
Bari, Italy [54]		Solar Collectors	Seawater		5		
Island Of Cape Verde [44]	1999	Solar Pond			5		Atlantis (Auto flash), 30–95 °C TBT
Suez, Egypt [45]	2005	FPC		2.39 m^2 FPC	0.009		PR 0.7–0.9, 40–60 °C TBT, RR 0.6%

that for a solar fraction of 50%, the water cost were in the range of 3–4.5\$/m^3 for fuel cost of 3–10\$/GJ.

Table 1 presents the list of solar MSF desalination plants along with a summary of their performance parameters.

3.2. Multi-Effect Distillation (MED)

Most of large scale solar thermal plants are based on MED because of its low TBT requirements along with low specific energy consumption requirements as compared to MSF. In MED, water evaporates on the outside of heated tubes based on its saturation pressure. It then passes to the next effects for additional vapor production.

In 1984, MED plant powered by flat plate collectors was installed in Abu Dhabi [55]. The plant consisted of a vertical multiple-effect evaporator with 18 effects. Pre-heating was employed in each effect to increase the efficiency of the process. The plant achieved specific energy consumption of 50 kWh/m^3 which is comparable to conventional MED plants with minimal maintenance problems. A water cost of around 7–10\$/m^3 was estimated mostly due to solar collector cost.

The MED plant of Plataforma Solar de Almeria is another major effort in indirect solar desalination. The plant was installed in 1988 [56]. It was a MED-TVC plant powered by a PTC field designed for power generation. The plant proved the high reliability of MED process with small startup time. The GOR of the plant was in the range of 9.3–14 depending on the steam pressure. It also had a high recovery rate of around 37% comparable to RO process. In 1991, a double-effect heat absorption pump was added to utilize the low-grade waste heat from the plant. This resulted in reduction of electric and thermal energy consumption by 44% and 12% respectively. In 2004, a dedicated 500 m^2 PTC field with gas-boiler backup was attached to the MED plant to demonstrate the economic viability of the plant [57].

Another hybrid MED-TVC plant was installed at University of Ancona, Italy in 1997 [58]. The plant was capable of operating in the MED-TVC mode or in the TVC only mode. The main features of the plant were suction of non-condensable gas from the last stage, low fluid and vapor velocities allowed use of simple filters and less damage to tubes and low running temperatures reduced scale formation. A full titanium desalination unit was designed to assess the benefits of high heat transfer, reduced chemical requirements, improved plant life and minimal environmental impact versus higher cost.

The main parameter affecting water cost obtained from desalination plants depends strongly on the energy cost. A detailed economical analysis of a small scale solar-MED plant is presented in [59]. A water cost of 8.3–9.3\$/m^3 for a 100 m^3 solar-MED with fossil fuel backup is suggested. According to the analysis small scale solar-MED plant are economically viable for a 10\$/GJ fossil fuel energy price and a collector cost of 200\$/m^3. An economic comparison between solar collector powered MED and PV powered seawater

Table 2
Solar-MED desalination plants.

Location	Year	Energy source	Feed water type	Energy source details	Capacity (m^3/d)	SEC (kWh/m^3)	Specific plant details
Takami Island, Japan [63]	1977	ETC-FPC	Seawater	336 m^2 ETC, 185 m^2 FPC, 38 m^3 stratified hot water storage and 25 m^3 mixing type water storage	20		16 effect horizontal tube, air-bubbling type ED, ETC used for MED and FPC for ED, RR 24.5%
Abu Dhabi, UAE [55]	1984	ETC	Seawater	1862 m^2, 300 m^3 of stratified hot water storage	80	50	18 effect with preheating in each stage, GOR 12.4, RR 12%, water cost 7–10$/$m^3$
El Paso, USA [64]	1987	Solar Pond	Seawater	3000 m^2 with 3.75 m depth			24 stages falling film MED
Plataforma Solar De Almeria, Spain [56]	1988	PTC	Seawater	2672 m^2, 115 m^3 thermocline hot water storage	72	3.3–5 (electric) 57.5–70.4 (thermal)	14 effect vertical stack, hydro-ejectors vacuum system, GOR 9.3 to 10.7 at low pressure steam 0.28 bar and increases to 12–14 if use high pressure steam 16–26 bar, RR37.5%, Absorption pump addition resulted in 44% and 12% reduction in thermal and electric consumption respectively
Le Desired Island, France [65]		ETC			40		14 effect
University Of Ancona, Italy [58]	1997	Solar Pond	Seawater	625 m^2 with 3.5 m depth	30	8 (electric) 194 (thermal) for MED, 2.5 (electric) 111 (thermal) for TVC	GOR 5.73 for TVC, RR 5.7% for MED and 11.4 for TVC
Near Dead Sea, Israel [66]		Solar Pond			3000		
Plataforma Solar De Almeria, Spain [57]	2004	CPC	Seawater	500 m^2, gas boiler back up with 30% continuous operation	72	3.3–5 (electric) 57.5–70.4 (thermal)	14 stages, double-effect absorption heat pump to enhance system efficiency, hydro-ejectors vacuum system, PR 11, water cost 2.86$/$m^3$

RO (PV-SWRO) plant with both plants backed by a diesel generator is presented in [60]. It is suggested that PV-SWRO plant is always cheaper and more environmentally friendly than a solar-MED plant. Also, PV-SWRO plants become economically feasible for a fuel energy cost of 26$/GJ and PV array cost of 3$/Wp. In [61], an economic comparison between large-scale solar-MED and PV-SWRO plant is presented. It is suggested that for capacities higher than 1000 m^3/d thermally driven MED is cheaper than PV powered RO plant. Based on the assumptions, the estimated specific plant cost for a solar-MED plant varies between 5000–8600$/$m^3$/d. It is suggested that for large-scale plants, water cost from a solar MED plant can be reduced to 2$/$m^3$. An economic analysis of a conventional solar-MED plant and a solar-MED plant coupled with an absorption heat pump is presented in [62] and a similar cost is suggested for solar-MED plants.

Table 2 presents the list of solar MED desalination plants along with a summary of features of these plants.

3.3. Reverse Osmosis (RO)

RO is the second most dominant desalination technology. In RO, saline water is fed to the porous membranes at high pressure. Due to hydrophilic nature of membranes, only water is allowed to pass through. RO processes have a high recovery ratio (RR) > 50% and high salt rejection (SR) > 90% with low specific energy consumption. As compared to thermally driven technologies, the energy requirement for conventional RO plants is around 5 kWh/m^3 for large scale plants. However, RO membranes are susceptible to fouling and scaling necessitating pre-treatment which results in higher maintenance cost and environmental impact.

PV powered RO plant was first investigated on a commercial scale in Saudi Arabia in 1981 [67]. The system successfully desalinated seawater of 42,800 ppm at a production rate of 3.2 m^3/d. Due to unavailability of energy recovery devices the specific energy consumption was in the range of 16.1–19.7 kWh/m^3.

In Greece [68,69], coupling of PV and wind with an RO process for seawater desalination was investigated in 2003. The system consisted of 3.96 kWp PV panels separated in three sub-arrays of 12 modules with manually adjustable tilt. A 900 Wp wind turbine was also installed. The PV and wind turbine systems were linked to a battery bank of 44.4 kWh electrical storage. The system produced 3.12 m^3/d with energy consumption of 16.5 kWh/m^3. No energy recovery device was installed to cut down costs. Water costs from the unit were estimated to be in the range of 23–27$/$m^3$.

Investigation on the benefit of using batteries for PV powered RO system coupled with an energy recovery device was done in Greece [33,70]. The system was used to desalinate feed water of 35,000 ppm with an average production rate of .8 m^3/d without using batteries. The specific energy consumption of the system was 4.3–4.6 kWh/m^3 which suggested using energy recovery devices in remote desalination systems. However, the increase in production due to batteries was not significant. The water cost from the system was 7.8$/$m^3$ without using batteries and 8.3$/$m^3$ for a battery based system.

Table 3
Solar-RO desalination plants.

Location	Year	Energy source	Feed water type	Energy source details	Capacity (m^3/d)	SEC (kWh/m^3)	Specific plant details
Cadarache, France [21]	1978	FPC-heat engine	Brackish Water	223 m^2 FPC, 3 kW heat engine	15		Feed water salinity 2000 ppm
Concepcion Del Oro, Mexico [74]	1980	PV	Brackish Water	2.5 kWp PV	1.5	6.9	Feed water salinity 3000 ppm, RR 37%
Las Barranas, Mexico [51]	1980	PV	Seawater	250 kWp PV	20		
Jeddah, Saudi Arabia [67,75]	1981	PV	Seawater	8 kWp PV, 46.56 kWh battery	3.2	16.1–19.7	Feed water salinity 42,800 ppm, RR 22%
El Hamarawein, Egypt [21]	1981	FPC-heat engine	Brackish Water	10 kW heat engine	54		Feed water salinity 3500 ppm
Perth, Australia [76,77]	1982	PV	Brackish Water	1.2 kWp PV, 4.3 kWh battery storage	0.4–0.7	4–5.8	
Citius, Indonesia [78]	1983	PV	Brackish Water	24.5 kWp (pump) 1.22 kWp (control) PV, 132 kWh (pump) and 4.8 kWh (control) battery	12	8	Feed water salinity 3500 ppm, RR 35%, SR 98.5%, water cost 3.68$/$m^3$
Vancouver, Canada [75,79]	1984	PV	Seawater	4.8 kWp PV	4	<4	Price estimate for variable speed pump w/o battery and with energy recovery, feed water salinity 3300 ppm, water cost 9$/$m^3$
El Hamarawein, Egypt [36]	1986	PV	Brackish Water	19.84 kWp (pump) 0.64 kWp (control equipment) PV, 208 kWh battery	53	0.89	Feed water salinity 3500 ppm, RR 51%
Hassi Khebi, Algeria [75,80,81]	1988	PV	Brackish Water	2.59 kWp PV, 60 kWh battery	24	1.38–2.77	Feed water salinity 3000 ppm, RR 24–40.7%
Doha, Qatar [82]	1988	PV	Seawater	11.2 kWp PV	5.7	10.6	Feed water salinity 3500 ppm
Wanoo Roadhouse, Australia [22]		PV	Brackish Water	6 kWp PV			
University Of Almeria, Spain [23]	1988	PV	Brackish Water	23.5 kWp PV, 2240 Ah 190–254 V battery	2.48		Feed water salinity 2690–4030 ppm
Gillen Bore, Australia [76]	1993	PV	Brackish Water	0.52 kWp PV	1.2		Feed water salinity 1600 ppm
Lempedusa Island, Italy [22]		PV	Seawater	100 kWp PV	3 + 2 m^3/h		Water cost 9.75$/$m^3$
St. Lucie Inlet State Park Florida, USA [29]	1995	PV	Seawater	2.7 kWp PV, diesel generator	0.64	13	Feed water salinity 3200 ppm, RR 10%
Lipari Island, Italy [22]		PV	Seawater	63 kWp PV	2 m^3/h		
Sadous Riyadh, Saudi Arabia [83,84]	1995	PV	Brackish Water	10.1 kWp PV, 264.24 kWh battery	10 + 5 (with still)	<18	Feed water salinity 5800 ppm, attachment of solar still to plant was proposed with RO blow down as feed to still, 1449 m^2 still area, water at 3$/$m^3$ from still at 35–45% still efficiency
Heelat Ar Rakah, Oman [85]	1995	PV	Brackish Water	3.25 kWp PV, 9.6 kWh battery	5–7.5	2.45	Feed water salinity 1000 ppm, water cost 6.25$/$m^3$
Mudroch University, Australia [37]	1997	PV	Brackish Water	0.12 kWp PV	0.4		Venco manufacturer, commercial unit, feed water salinity 5000 ppm, RR 16–25%

Table 3 (*Continued*)

Location	Year	Energy source	Energy source details	Feed water type	Capacity (m^3/d)	Specific energy consumption (kWh/m^3)	Specific plant details
Canary Island, Spain [86]	1998	PV	Seawater	4.8 kWp PV, 59.52 kWh battery storage	0.8–4.2	18–19	Feed water salinity 35,000 ppm, RR 14%, water cost 16–17$/$m^3$
Lisbon, Portugal [75,87]	2000	PV	Brackish Water	0.15 kWp PV	0.08	25.6–32.4	Feed water salinity 2000–5000 ppm, RR 1.8–2.4%, SR 90–94%
Haifa, Israel [88]	2000	PV, wind	Brackish Water	3.5 kWp PV, 0.6 kWp wind, 36 kWh battery	3		Feed water salinity 4000 ppm, RR 50%, SR 98%
Ceara, Brazil [75]	2000	PV	Brackish Water	1.1 kWp PV, 9.6 kWh battery	6	3	Feed water salinity 1200 ppm, RR 27%, water cost 12.76$/$m^3$
White Cliffs, Australia [89]	2002	PV	Brackish Water	0.34 kWp PV	0.5	8	Feed water salinity 3500 ppm, RR 10–25%, SR 93–95%,
Keratea, Greece [68,69]	2003	PV-wind	Seawater	3.96 kWp PV, 0.9 kWp wind, 44.4 kWh battery	3.12	16.5	Feed water salinity 37,700 ppm, RR 13%, water cost 23–27$/$m^3$
Massawa, Eritrea [90]	2003	PV	Seawater	2.4 kWp PV with single-axis tracking	3		Spectra Clark pump energy recovery, lab test data used, feed water salinity 40,000 ppm, water cost 3$/$m^3$
Baja California Sur, Mexico [51]	2003	PV	Seawater		19	2.6	Tested Spectra Clark pump, pressure exchanger and Danfoss axial piston motors, as low as 2.6 kWh/m^3 achieved
Canary Island, Spain [91]	2004	PV	Seawater	5.6 kWp PV with tracking, 41 kWh battery	10	2.54	Pressure Exchanger, feed water salinity 35,000 ppm, RR 36%
Agricultural University Of Athens, Greece [57,69]	2004	PV-wind	Seawater	0.846 kWp PV, 1 kWp wind, 7.56 kWh battery	2.2	3.3–5.2	Spectra Clark pump, feed water salinity 35,000 ppm, RR 10%, SR 99.2%, water cost 8–11$/$m^3$
Canary Island, Spain [91]	2005	PV-wind	Seawater	0.6 kWp PV, 0.89 kWp wind, 21 kWh battery	1	3.74	Energy recovery device, RR 18%,
North West Of Sicily, Italy [92]	2005	PV	Seawater	125 kWp PV, 160 kVA diesel generator, 1236 kWh battery	36	4.86	Pelton turbine recovery
Agricultural University Of Athens, Greece [33,93]	2005	ETC-heat engine	Seawater	162 m^2 ETC, 100 kW heat engine, R-134a as working fluid	1.8	2–3	Energy recovery by turbine, feed water salinity 35,000 ppm, RR 15%, water cost 15$/$m^3$
Cooper Pedy, Australia [94]	2005	PV	Brackish Water	3.2 kWp PV	0.764	3.2	Feed water salinity 7400 ppm, RR 17.5%, SR 96%
Rajasthan, India [95]	2006	PV	Brackish Water	2.5 kWp PV	3.6		Feed water salinity 6000 ppm, SR > 95%
Solarflow, Australia [96]		PV	Brackish Water	0.12 kWp PV	0.4		Feed water salinity 5000 ppm
Agricultural University Of Athens, Greece [33,70]	2006	PV	Seawater	0.846 kWp PV, 7.56 kWh battery	0.8 (w/o battery), 0.9 (with battery)	4.3–4.6	Energy recovery by Clark type pump, feed water salinity 35,000 ppm, RR 8%, SR 99.2%, water cost 7.8$/$m^3$ (w/o battery) 8.3$/$m^3$ (with battery)
Marett Island, Italy [54]		PV	Seawater		5		
San Nicola, Italy [54]		PV	Seawater		12		

Table 3 (*Continued*)

Location	Year	Energy source	Energy source details	Feed water type	Capacity (m^3/d)	Specific energy consumption (kWh/m^3)	Specific plant details
Ras Ejder, Libya [97]	2006	PV-wind-diesel	Seawater	50 kWp PV, 275 kWp wind, grid back up	300	4.3	Energy recovery by PX, feed water salinity 42,000 ppm, RR 35%, water cost 3$/$m^3$
Ksar Chilene, Tunisia [57]	2006	PV	Brackish Water	10.5 kWp PV, 72 kWh battery	50	8	Building containing desalination unit and control equipment half-buried and use solar panel shade to provide passive cooling, feed water salinity 3500 ppm, RR 70%
Irbid, Jordan [98]	2007	PV	Brackish Water	0.136 kWp PV, 0.744 kWh battery	0.192	1.3–2.7 (w/o battery- battery)	Feed water salinity 720 ppm, RR 37%, SR 98%, water cost 10$/$m^3$ (w/o battery) 13$/$m^3$ (with battery)
Fethiye Area, Turkey [57]	2007	PV	Brackish Water	6 kWp PV, 4.8 kWh battery	2	15	RR 15%, water cost 25$/$m^3$
Tangarfa, Agadir, Azla and Marrakech, Morocco [91]	2008	PV	Brackish Water	4 kWp PV	8		4 systems were installed, feed water salinity 2500–8700 ppm
Alexandria University, Egypt [99]	2009	PV-Wind-diesel	Brackish Water	7.6 kWp PV, 5 kW wind, 5 kVA diesel generator	30		Feed water salinity 10,000 ppm

Use of solar thermal collectors to power RO processes has been tried as early as 1978. Heat collected from the solar collectors is used for running a heat engine based on the Rankine cycle. The hot fluid is heated up in the collector which is then expanded in a turbine providing shaft power. A techno-economic comparison of a RO system powered by PV panels and a RO system powered by solar-rankine cycle is presented in [33]. The solar-Rankine system consisted of 162 m^2 of ETC with a 100 kW heat engine. The energy consumption of the solar-Rankine system was 2–3 kWh/m^3 as compared to 4.3–4.6 kWh/m^3 of PV based system. However, the water cost of solar-Rankine system was around 15$/$m^3$ as compared to 8.3$/$m^3$ for PV based system. The higher cost of water produced by a solar-Rankine system is due to higher energy system cost which is 66% of the total system cost as compared to 31% for PV powered system.

The factors affecting PV-RO water cost are capital cost of PV array and battery, inclusion of energy recovery device, type of feed water, and type of RO unit. Also as RO unit is sensitive to pre-treatment, in addition to normal operating costs such as maintenance, personnel and chemical cost; cost of membrane replacement and membrane performance degradation over time are also added. In [71], economic comparison between a PV-RO plant, PV-RO plant with diesel generator backup and a diesel generator powered RO unit is presented. A water cost of around 7$/$m^3$ for a 44 m^3/d is estimated. It is suggested that a PV RO plant is economically competitive for fossil energy price of 14$/GJ and PV panel cost of 8$/Wp. A methodology for designing of standalone PV-RO plant is presented in [72]. The study was done in 1998 and high water cost of around 30$/$m^3$ is given due to high cost of PV panels. A recent detailed economic analysis and comparison between PV powered and diesel generator powered RO desalination is presented in [35]. It is estimated that the cost of PV-SWRO is system is 36% higher than diesel-RO system. For large-scale plants having capacity of greater than 1000 m^3/d, the specific plant cost is in the range of 4500–6200$/$m^3$/d with estimated water cost of <2$/$m^3$ owing to the reduction of high efficiency PV module cost [61]. For solar-rankine RO systems, a detailed economic analysis of a two stage rankine cycle and comparison with PV RO system either directly powered or coupled with battery and single stage rankine cycle is presented in [73]. For a rankine system, around 66% of cost is associated with energy system with rankine system taking 25% of this cost share. Water cost of 9$/$m^3$ is estimated for a two stage solar-rankine RO cycle which is comparable to PV-SWRO systems.

Table 3 presents the list of solar RO desalination plants along with a summary of features of these plants.

3.4. Membrane Distillation (MD)

Membrane Distillation is a thermally driven technique that combines the concept of distillation and membrane desalination. It has recently started attracting interest due to its benefits of low temperature requirement, resistance against fouling and scaling, elimination of chemical pre-treatment and possibility of intermittent operation without storage [40]. MD is reported to have distillate output 4.5 times that of solar still for the same thermal energy input [39]. In MD processes, heated feed water flows on one side of the hydrophobic membrane. Due to vapor pressure difference across the membrane, water vapor permeates and is condensed on the other side of the membrane. There are currently four methods of collection of this water vapor permeate; Direct Contact (DCMD), Air Gap (AGMD), Sweeping Gas (SGMD) and Vacuum (VMD). In DCMD, cold water (distilled water) flows on the side of the membrane opposite to saline water side resulting in condensation of water vapor while in AGMD water vapor condenses on a cold plate cooled by water of any salinity. Advantage of DCMD is that gas gap between membrane interface and condensate stream

Table 4
Solar-MD desalination plants.

Location	Year	Energy source	Feed water type	Energy source details	Capacity (m^3/d)	SEC (kWh/m^3)	Specific plant details
Hzag, Tunisia [66]		Solar Collectors			0.1–0.35		
University of New South Wales, Australia [29,102]	1991	FPC	Seawater	3 m^2 FPC	0.05	55.6 (thermal and electric combined)	Process efficiency 17 l/d/m^2 of collector area
Island of Ibzia, Spain [103]	1993	ETC	Seawater	51 m^2 ETC, 10 m^3 hot water storage	2	150–200	RR 5%
California, Usa [54,104]		Solar Pond					
Tokyo, Japan [29,105]	1994	Solar Collectors and PV	Seawater		0.96		PV for pumps
El Paso, USA [106]	1999	Solar Pond	Seawater	3000 m^2 Solar Pond with 3.75 m depth	0.4		Feed water salinity 35,000 ppm
Canary Island, Spain [91]	2003	FPC and PV	Seawater	6 m^2 FPC, 0.08–0.096 kWp PV	0.08	144	1 membrane module with high internal heat recovery, feed water salinity 35,000 ppm,
Alexandria, Egypt [104]	2005	FPC	Brackish Water	5.73 m^2 FPC	0.064	647	Single-loop system, feed water salinity 670 ppm, SR 99.5%, process efficiency 90%
Kelaa De Sraghna, Morocco [38,40]	2005	FPC		5.73 m^2 FPC			Single-loop system
Porto Santo Island, Portugal [54]		Direct Heating			300		
Gran Canary, Spain [38,40]	2005	FPC-PV	Seawater	90 m^2 FPC, 4 m^3 hot water tank, 1.92 kWp PV, no battery	0.15	100–200	5 membrane module, PV for pumps, two loop system, double glass collector with anti-reflective coating, feed water salinity 35,000 ppm, RR 3.6%
Irbid, Jordan [107]	2005	FPC-PV	Brackish Water	5.73 m^2 FPC, 0.106 kWp PV,	0.1	200–300	1 membrane module with high internal heat recovery, RR 1–4%, GOR 0.3–0.9
Aqaba, Jordan [100]	2006	FPC-PV	Seawater	72 m^2 FPC, 1.44 kWp PV, 3 m^3 water storage, battery storage	0.44	200–300	4 membrane modules, PV for pumps, GOR 0.4–0.7, two loop system, feed water salinity 55,000 ppm, RR 3–4.5%
Tenerife, Spain [38]	2007	FPC-PV			0.12		Feed water salinity 35,000 ppm

Table 5
Solar-ED desalination plants.

Location	Year	Energy source	Feed water type	Energy source details	Capacity (m^3/d)	SEC (kWh/m^3)	Specific plant details
Takami Island, Japan [63]	1977	ETC-FPC	Seawater	336 m^2 ETC, 185 m^2 FPC, 38 m^3 stratified hot water storage and 25 m^3 mixing type water storage	10 (MED) 10 (ED)		16 effect horizontal tube, air-bubbling type ED, ETC used for MED and FPC for ED, RR 24.5%
Spencer Valley, Mexico [36,111]	1986	PV	Brackish Water	1 kWp PV with tracking, 2.3 kWp PV stationary	2.8	0.82	Tracking PV's for controls and stationary PV for ED, feed water salinity 1000 ppm, water cost 16$/m^3$
Thar Desert, India [36,112]	1986	PV	Brackish Water	0.45 kWp PV	1	1 kWh/kg of salt removed	42 cell pairs, feed water salinity 5000 ppm
Ohsima Island, Japan [36,111]	1986	PV	Seawater	25 kWp PV	10		250 cell pairs, partial desalinated water storage and perform full desalination when small solar power available, water cost 5.8$/m^3$
Fukue City, Japan [29,113]	1990	PV	Brackish Water	65 kWp PV, 1.2 Ah battery storage	200	0.6–1	Feed water salinity 700 ppm
New Mexico, Mexico [114]	1996	PV	Brackish Water	2.3 kWp PV, 600 Ah battery	18	0.8	Feed water salinity 900 ppm
Isa Town, Bahrain [108]	2002	PV	Brackish Water	0.132 kWp PV	1.14		24 cell pairs, feed water salinity 3300 ppm, SR 30–50%
University of Alicante, Spain [110,115]	2006	PV	Brackish Water	0.272 kWp PV	1.32		80 cells, 550 cm^2 unit cell area, feed water salinity 2000 ppm

is narrow resulting in high temperature drop across membrane and consequentially higher mass transfer but also higher energy consumption due to higher water flow rate as compared to AGMD. In SGMD, gas such as dry air flows on the other side of the membrane sweeping vapor from the membrane. This is then condensed in a condenser located outside of the membrane module. The vapor flow through the membrane is higher as compared to AGMD due to turbulence achieved by the circulating gas. In VMD, a vacuum creates the necessary driving force for the vapor. The vapor flux can be increased by applying vacuum even at low temperature difference. Similar to SGMD, VMD also needs a condenser for condensing this vapor along with high electricity consumption [38]. Only DCMD and AGMD were found to be used for solar desalination according to published literature.

In 2003, a project with the name of SMADES funded by the European Commission was carried out to assess desalination systems with low maintenance needs and experimentally investigate the performance of such systems. MD plants were installed in Spain, Morocco, Egypt and Jordan using AGMD membranes developed by Fraunhofer Institute for Solar Energy, Germany [100]. The system installed in Jordan was the largest having an actual average daily productivity of 0.44 m^3/d. It consisted of a two-loop system for supplying heat. The advantage of the system was that seawater was heated through a heat exchanger and normal solar collectors were used. The effects of solar radiation and feed flow rate were examined. The system successfully desalinated seawater of 55,000 ppm with specific energy consumption in the range of 200–300 kWh/m^3.

In [101], economic analyses of small and medium scale solar-MD plants are provided. The economic analysis is based on the 0.1 m^3/d and 0.5 m^3/d plants installed in Jordan. Detailed actual capital costs are provided for each of the plant's components. Membrane cost and their replacement costs are suggested to be the main cost controlling parameters. A water cost of 15$/m^3$ and 18$/m^3$ for compact and medium-scale solar-MD plants is estimated. It is anticipated that due to use of corrosion resistant materials and resistance against fouling, longer plant lives can reduce these costs by 3$/m^3$ for each system.

Table 4 presents the list of solar MD desalination plants along with a summary of features of these plants.

3.5. Electrodialysis (ED)

ED based desalination is usually used for treatment of brackish or waste-water. In ED, a DC current is supplied to the Electrodialysis cell. Positive ions present in the water move towards the cathode while the negative ions move towards the anode. In an ED stack, several of such cells are placed in parallel to the flow separated by flow spacers [108]. The streams in alternating spacers contain diluted and concentrated water. ED was first commercially used in 1953 at an oilfield campsite in Saudi Arabia [109]. ED became Electrodialysis Reversal (EDR) in 1974 when the effect of reversing DC electric field to membrane stack was investigated. Field reversing resulted in driving salt scale off the membranes. The frequency and duration of field reversing depends on the turbidity and salt concentration of feed water. EDR eliminates the need to feed either acid or anti-scalant chemicals into the desalination process which is a major advantage of EDR over RO.

The plant installed in Fukue City, Japan in 1990 is the largest solar powered ED plant with average distillate production of 200 m^3/d. The plant consisted of a 65 kWp PV array with 1.2 Ah of storage. The distillate production ranged from 130–370 m^3/d with energy consumption of 0.6–1 kWh/m^3.

Recent experiments with ED consist of an EDR system in Bahrain and at the University of Alicante, Spain. In Bahrain, various solutions of concentrations ranging from 1000–5000 ppm were tested. A production rate of 1.14 m^3/d was achieved with a SR of >95%. It was concluded that increasing the feed water temperature results in higher SR [108]. In Spain [110], effect of variation in PV power on ED process was investigated.

A recent detailed economic analysis and comparison between PV powered and diesel generator powered ED desalination is presented in [35]. It is estimated that the capital cost of PV-ED system is 30% higher than diesel-ED system. The water cost of PV-ED system is estimated to be 3$/m^3$ for a 50 m^3/d capacity plant. It is suggested

Table 6
Reported performance ranges of indirect solar desalination plants.

Technology	Feed water type	Specific energy consumption (kWh/m^3)	Recovery ratio (%)	Water cost ($/m^3)
MSF	Seawater, brackish water	81–144 (thermal)	0.6–6	1–5
MED	Seawater, brackish water	50–194 (thermal)	6–38	2–9
MD	Seawater, brackish water	100–600 (thermal)	3–5	13–18
RO	Seawater, brackish water	1.2–19 (electric)	10–51	3–27
ED	Brackish water	0.6–1 (electric)	25–50	3–16

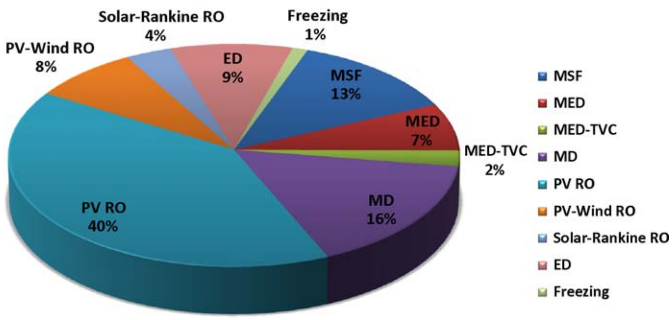

Fig. 3. Share of desalination technologies in indirect solar desalination plants installed worldwide.

that feed water concentration and PV cost are the main parameters affecting water cost.

Table 5 presents the list of solar ED desalination plants along with a summary of features of these plants.

3.6. Freezing

Freezing is a novel desalination concept in which saline water is frozen using refrigeration processes such as vapor compression, absorption-refrigeration or vacuum-freezing ejector-absorption. In vapor compression, refrigerant is used to bring feed water to its freezing temperature. This process has a very high thermal efficiency around three times the electrical input to the system. In vacuum-freezing ejector-absorption, a vacuum is created by a steam ejector which brings the feed water to its triple point, thus freezing the water with some evaporation. The vapors generated are absorbed in a caustic solution and heated. The ice produced is then washed. After washing the ice, heated vapors are used to melt the ice. Some proposals for solar-assisted freezing desalination based on vapor compression and vacuum-freezing ejector-absorption are given in [116,117].

In 1982, a seawater desalination plant based on freezing was installed in Saudi Arabia [118]. It consisted of 43,800 m^2 area of dish collectors with 10 day salt storage. An ammonia based vapor compression cycle along with LiBr absorption refrigeration was used for freezing. Indirect contact freezing was employed which meant that there was no contact between process water and saline water. The capacity of the system was in the range of 48–178 m^3/d with energy consumption of 108 kWh/m^3. The plant was shut down in 1989 because it was not economically feasible.

4. Conclusion

Indirect solar desalination is a promising way of meeting water demand in remote areas and as a way to reduce the carbon footprint of commercial desalination. Membrane technologies such as RO and ED are currently the most cost-competitive solar desalination technologies approaching conventional desalination water costs. However solar-MED is recommended for large-scale solar desalination plants because of low water cost as estimated in [59].

Fig. 3 presents the share of each desalination technology alongwith its energy source. It can be observed that out of 87 indirect solar desalination plants installed worldwide, 52% are RO based while 13% and 9% of these plants are based on conventional thermal desalination technologies i.e. MSF and MED. ED shares 9% of the total and is recommended for desalination of brackish water because of its minimal energy requirements.

Table 6 presents the energy requirements, RR and water cost of indirect solar desalination plants. It can be observed that RR of PV powered technologies i.e. RO and ED is higher as compared to thermally driven desalination technologies. Low energy requirements and high RR are the reasons of high proliferation of RO among other desalination technologies despite their lower water cost.

Recent developments in indirect solar desalination have focused on MD as it combines the advantages of both membrane and thermal desalination technologies such as operation on thermal energy, ability to desalinate high salinity water, minimal pre-treatment and fouling resistant. Although currently its energy requirements are still high with low RR, the distillate output from MD is estimated to be 4.5 times the output from a solar still.

References

[1] DesalData. DesalData [Online]. Available: www.desaldata.com.
[2] Gordes JN, Perlin J. An historical and prospective review of solar water purification.
[3] Tiwari GN, Singh HN, Tripathi R. Present status of solar distillation. Solar Energy 2003;75(5):367–73.
[4] Fath HES. Solar distillation: a promising alternative for water provision with free energy, simple technology and a clean environment. Desalination 1998;116(1):45–56.
[5] Sampathkumar K, Arjunan TV, Pitchandi P, Senthilkumar P. Active solar distillation—a detailed review. Renewable and Sustainable Energy Reviews 2010;14(6):1503–26.
[6] Goosen MFA, Sablani SS, Shayya WH, Paton C, Al-Hinai H. Thermodynamic and economic considerations in solar desalination. Desalination 2000;129(1):63–89.
[7] Arjunan TV, Aybar HS, Nedunchezhian N. Status of solar desalination in India. Renewable and Sustainable Energy Reviews 2009;13(9):2408–18.
[8] Kaushal A, Varun. Solar stills: a review. Renewable and Sustainable Energy Reviews 2010;14(1):446–53.
[9] Velmurugan V, Srithar K. Performance analysis of solar stills based on various factors affecting the productivity—a review. Renewable and Sustainable Energy Reviews 2011;15(2):1294–304.
[10] Kabeel AE, Hamed AM, El-Agouz SA. Cost analysis of different solar still configurations. Energy 2010;35(7):2901–8.
[11] Le Goff P, Le Goff H.Proc. New Technologies for the Use of Renewable Energy Sources in Water Desalination. 1991. p. 99–114.
[12] Khalil A. Dehumidification of atmospheric air as a potential source of fresh water in the UAE. Desalination 1993;93(1–3):587–96.
[13] Bulang WG. Solar water recovery from air. Solar Energy International Progress 1978;3:1526–44.
[14] Aly SE. Humidity water vapor collection by absorption cooling machines. Desalination 1989;73:139–65.
[15] Abualhamayel HI, Gandhidasan P. A method of obtaining fresh water from the humid atmosphere. Desalination 1997;113(1):51–63.
[16] Parekh S, Farid MM, Selman JR, Al-hallaj S. Solar desalination with a humidification-dehumidification technique—a comprehensive technical review. Desalination 2004;160(2):167–86.
[17] Narayan GP, Sharqawy MH, Summers EK, Lienhard JH, Zubair SM, Antar MA. The potential of solar-driven humidification–dehumidification desalination for small-scale decentralized water production. Renewable and Sustainable Energy Reviews 2010;14(4):1187–201.
[18] Müller-Holst H. Solar thermal desalination using the Multiple Effect Humidification (MEH) method. In: Solar desalination for the 21st century; 2007. p. 215–25.

[19] Al-Hallaj S, Parekh S, Farid MM, Selman JR. Solar desalination with humidification–dehumidification cycle: review of economics. Desalination 2006;195(1–3):169–86.
[20] Kalogirou SA. Solar thermal collectors and applications. Progress in Energy and Combustion Science 2004;30(3):231–95.
[21] Libert JJ, Maurel A. Desalination and renewable energies—a few recent developments. Desalination 1981;39:363–72.
[22] Delyannis EE. Status of solar assisted desalination: a review. Desalination 1987;67:3–19.
[23] Kalogirou SA. Seawater desalination using renewable energy sources. Progress in Energy and Combustion Science 2005;31(3):242–81.
[24] Garcia-Rodriguez L. Seawater desalination driven by renewable energies: a review. Desalination 2002;143(2):103–13.
[25] Tzen E, Morris R. Renewable energy sources for desalination. Solar Energy 2003;75(5):375–9.
[26] Hanafi A. Desalination using renewable energy sources. Desalination 1994;97(1–3):339–52.
[27] Mathioulakis E, Belessiotis V, Delyannis E. Desalination by using alternative energy: review and state-of-the-art. Desalination 2007;203(1–3): 346–65.
[28] Eltawil MA, Zhengming Z, Yuan L. A review of renewable energy technologies integrated with desalination systems. Renewable and Sustainable Energy Reviews 2009;13(9):2245–62.
[29] Thomas KE. Overview of village scale, renewable energy powered desalination. Golden, CO, United States: National Renewable Energy Lab; 1997.
[30] Van der Bruggen B, Vandecasteele C. Distillation vs. membrane filtration: overview of process evolutions in seawater desalination. Desalination 2002;143(3):207–18.
[31] Delgado-Torres AM, García-Rodríguez L. Status of solar thermal-driven reverse osmosis desalination. Desalination 2007;216(1–3):242–51.
[32] García-Rodríguez L, Delgado-Torres AM. Solar-powered rankine cycles for fresh water production. Desalination 2007;212(1–3):319–27.
[33] Manolakos D, Mohamed ES, Karagiannis I, Papadakis G. Technical and economic comparison between PV-RO system and RO-Solar rankine system. Case study: Thirasia island. Desalination 2008;221(1–3):37–46.
[34] Charcosset C. A review of membrane processes and renewable energies for desalination. Desalination 2009;245(1–3):214–31.
[35] Abraham T, Luthra A. Socio-economic & technical assessment of photovoltaic powered membrane desalination processes for India. Desalination 2011;268(1–3):238–48.
[36] Al-Karaghouli A, Renne D, Kazmerski LL. Technical and economic assessment of photovoltaic-driven desalination systems. Renewable Energy 2010;35(2):323–8.
[37] Banat F, Qiblawey H. Membrane desalination driven by solar energy. In: Solar desalination for the 21st century; 2007. p. 271–91.
[38] Koschikowski J, Wieghaus M, Rommel M. Membrane distillation for solar desalination. Seawater Desalination 2009:165–87.
[39] Koschikowski J, Wieghaus M, Rommel M. Solar thermal-driven desalination plants based on membrane distillation. Desalination 2003;156(1–3):295–304.
[40] Koschikowski J, Wieghaus M, Rommel M, Ortin VS, Suarez BP, Betancort Rodríguez JR. Experimental investigations on solar driven stand-alone membrane distillation systems for remote areas. Desalination 2009;248(1–3):125–31.
[41] Burgess G, Lovegrove K. Solar thermal powered desalination: membrane versus distillation technologies, 200. Canberra ACT: Centre for Sustainable Energy Systems, Department of Engineering, Australian National University; 2005.
[42] Moustafa SMA, Jarrar DI, El-Mansy HI. Performance of a self-regulating solar multistage flash desalination system. Solar Energy 1985;35(4):333–40.
[43] Lu H, Walton JC, Swift AHP. Desalination coupled with salinity-gradient solar ponds. Desalination 2001;136(1–3):13–23.
[44] Hoffman D. The application of solar energy for large-scale seawater desalination. Desalination 1992;89(2):115–83.
[45] Nafey AS, Mohamad MA, El-Helaby SO, Sharaf MA. Theoretical and experimental study of a small unit for solar desalination using flashing process. Energy Conversion and Management 2007;48(2):528–38.
[46] Miller JE. Review of water resources and desalination technologies. In: SAND0800. 2003.
[47] Suri RK, Al-Marafie AMR, Al-Homoud AA, Maheshwari GP. Cost-effectiveness of solar water production. Desalination 1989;71(2):165–75.
[48] García-Rodríguez L, Gómez-Camacho C. Conditions for economical benefits of the use of solar energy in multi-stage flash distillation. Desalination 1999;125(1–3):133–8.
[49] Mokhtar M, Ali MT, Bräuniger S, Afshari A, Sgouridis S, Armstrong PR, Chiesa M. Systematic comprehensive techno-economic assessment of solar cooling technologies using location-specific climate data. Applied Energy 2010;87(12):3766–78.
[50] Manwell JF, McGowan JG. Recent renewable energy driven desalination system research and development in North America. Desalination 1994;94(3):229–41.
[51] Bermudez-Contreras A, Thomson M, Infield DG. Renewable energy powered desalination in Baja California Sur, Mexico. Desalination 2008;220(1–3):431–40.
[52] García-Rodríguez L. Assessment of most promising developments in solar desalination. In: Solar desalination for the 21st century; 2007. p. 355–69.
[53] Abu-Jabal MS, Kamiya I, Narasaki Y. Proving test for a solar-powered desalination system in Gaza-Palestine. Desalination 2001;137(1–3):1–6.
[54] Belessiotis V, Delyannis E. Solar energy: some proposals for future development and application to desalination. Desalination 1996;105(1–2):151–8.
[55] El-Nashar AM, Samad M. The solar desalination plant in Abu Dhabi: 13 years of performance and operation history. Renewable Energy 1998;14(1–4):263–74.
[56] Milow B, Zarza E. Advanced MED solar desalination plants. Configurations, costs, future—seven years of experience at the Plataforma Solar de Almeria (Spain). Desalination 1997;108(1–3):51–8.
[57] Papapetrou M, Mohamed ES, Manolakos D, Papadakis G, Subiela VJ, Peñate B. Operating RE/desalination units. Seawater Desalination 2009:247–72.
[58] Caruso G, Naviglio A. A desalination plant using solar heat as a heat supply, not affecting the environment with chemicals. Desalination 1999;122(2–3):225–34.
[59] El-Nashar AM. The economic feasibility of small solar MED seawater desalination plants for remote arid areas. Desalination 2001;134(1–3):173–86.
[60] El-Nashar AM, Gobaisi DA, Makkawi B. Solar energy for desalination in the Arab World. In: Proceedings of ISES World Congress 2007, vol. I–vol. V. 2009. p. 213–21.
[61] Fiorenza G, Sharma VK, Braccio G. Techno-economic evaluation of a solar powered water desalination plant. Energy Conversion and Management 2003;44(14):2217–40.
[62] Garcia-Rodriguez L, Gomez-Camacho C. Thermo-economic analysis of a solar multi-effect distillation plant installed at the Plataforma Solar de Almeria (Spain). Desalination 1999;122(2–3):205–14.
[63] Noguchi T. Overview on thermal application of solar energy in Japan. Solar & Wind Technology 1985;2(3–4):155–71.
[64] Lu H, Swift AHP, Hein Jr HD, Walton JC. Advancements in salinity gradient solar pond technology based on sixteen years of operational experience. Journal of Solar Energy Engineering 2004;126:759.
[65] Madani AA. Economics of desalination for three plant sizes. Desalination 1990;78(2):187–200.
[66] Desalination guide using renewable energies. European Commission; 1998.
[67] Boesch WW. World's first solar powered reverse osmosis desalination plant. Desalination 1982;41(2):233–7.
[68] Tzen E, Theofilloyianakos D, Kologios Z. Autonomous reverse osmosis units driven by RE sources experiences and lessons learned. Desalination 2008;221(1–3):29–36.
[69] Mohamed ES, Papadakis G. A Stand Alone Sea Water Reverse Osmosis Desalination Unit Powered by Hybrid Wind-photovoltaic System for Rural Development and small Villages. In: Collection of Extent Abstracts of 2004 CIGR International Conference, vol. 2. 2004.
[70] Mohamed ES, Papadakis G, Mathioulakis E, Belessiotis V. A direct coupled photovoltaic seawater reverse osmosis desalination system toward battery based systems – a technical and economical experimental comparative study. Desalination 2008;221(1–3):17–22.
[71] Helal AM, Al-Malek SA, Al-Katheeri ES. Economic feasibility of alternative designs of a PV-RO desalination unit for remote areas in the United Arab Emirates. Desalination 2008;221(1–3):1–16.
[72] Tzen E, Perrakis K, Baltas P. Design of a standalone PV–desalination system for rural areas. Desalination 1998;119(1–3):327–33.
[73] Kosmadakis G, Manolakos D, Kyritsis S, Papadakis G. Economic assessment of a two-stage solar organic rankine cycle for reverse osmosis desalination. Renewable Energy 2009;34(6):1579–86.
[74] Petersen G, Fries S, Mohn J, Müller A. Wind and solar powered reverse osmosis desalination units-design, start up, operating experience. Desalination 1981;39:125–35.
[75] de Carvalho PCM, Riffel DB, Freire C, Montenegro FFD. The Brazilian experience with a photovoltaic powered reverse osmosis plant. Progress in Photovoltaics: Research and Applications 2004;12(5):373–85.
[76] Harrison DG, Ho GE, Mathew K. Desalination using renewable energy in Australia. Renewable Energy 1996;8(1–4):509–13.
[77] James WL. Design, construction and operation of a 1.2 kW photovoltaic reverse osmosis desalination plant. Presented at the solar energy coming of age: International Solar Energy Society; 1982.
[78] Effendi Y. Three years experiences for PVRO-desalination. In: Photovoltaic Specialists Conference, 1988. Conference Record of the Twentieth IEEE. 2002. p. 1194–9.
[79] Keeper BG, Hembree RD, Schrack FC. Optimized matching of solar photovoltaic power with reverse osmosis desalination. Desalination 1985;54:89–103.
[80] Sadi A, Kehal S. Retrospectives and potential use of saline water desalination in Algeria. Desalination 2003;152(1–3):51–6.
[81] Younos T, Tulou KE. Energy needs, consumption and sources. Journal of Contemporary Water Research & Education 2005;132(1):27–38.
[82] Block DL. Solar desalination of water. Cape Canaveral, Florida. USA Florida Solar Energy Center; 1989.
[83] Alawaji S, Smiai MS, Rafique S, Stafford B. PV-powered water pumping and desalination plant for remote areas in Saudi Arabia. Applied Energy 1995;52(2–3):283–9.
[84] Hasnain SM, Alajlan S. Coupling of PV-powered RO brackish water desalination plant with solar stills. Renewable Energy 1998;14(1–4):281–6.
[85] Al Suleimani Z, Nair VR. Desalination by solar-powered reverse osmosis in a remote area of the Sultanate of Oman. Applied Energy 2000;65(1–4): 367–80.

[86] Herold D, Horstmann V, Neskakis A, Plettner-Marliani J, Piernavieja G, Calero R. Small scale photovoltaic desalination for rural water supply-demonstration plant in Gran Canaria. Renewable Energy 1998;14(1–4):293–8.
[87] Joyce A, Loureiro D, Rodrigues C, Castro S. Small reverse osmosis units using PV systems for water purification in rural places. Desalination 2001;137(1–3):39–44.
[88] Weiner D, Fisher D, Moses EJ, Katz B, Meron G. Operation experience of a solar- and wind-powered desalination demonstration plant. Desalination 2001;137(1–3):7–13.
[89] Richards BS, Schäfer AI. Photovoltaic-powered desalination system for remote Australian communities. Renewable Energy 2003;28(13):2013–22.
[90] Thomson M, Infield D. A photovoltaic-powered seawater reverse-osmosis system without batteries. Desalination 2003;153(1–3):1–8.
[91] Subiela VJ, de la Fuente JA, Piernavieja G, Peñate B. Canary Islands Institute of Technology (ITC) experiences in desalination with renewable energies (1996–2008). Desalination and Water Treatment 2009;7:220–35.
[92] Scrivani A. Energy management and DSM techniques for a PV-diesel powered sea water reverse osmosis desalination plant in Ginostra, Sicily. Desalination 2005;183(1–3):63–72.
[93] Manolakos D, Kosmadakis G, Kyritsis S, Papadakis G. On site experimental evaluation of a low-temperature solar organic rankine cycle system for RO desalination. Solar Energy 2009;83(5):646–56.
[94] De Munari A, Capão DPS, Richards BS, Schäfer AI. Application of solar-powered desalination in a remote town in South Australia. Desalination 2009;248(1–3):72–82.
[95] Solar energy: applications. Barefoot College [Online]. Available: http://www.barefootcollege.org/sol_applications.asp [Accessed: 20 December, 2010].
[96] Maslin A, Annandale D, Saupin M. Decentralised water solutions Island infrastructure project. In: Proceedings of renewable energy sources for islands, tourism and water desalination conference. 2003. p. 287–94.
[97] Kershman SA, Rheinländer J, Neumann T, Goebel O. Hybrid wind/PV and conventional power for desalination in Libya—GECOL's facility for medium and small scale research at Ras Ejder. Desalination 2005;183(1–3):1–12.
[98] Qiblaweya H, Banata F, Al-Nassera Q. Laboratory setup for water purification using household PV-driven reverse osmosis unit. Desalination and Water Treatment 2009;7:53–9.
[99] Fath HES. Personal Communication; 2011.
[100] Banat F, Jwaied N, Rommel M, Koschikowski J, Wieghaus M. Performance evaluation of the 'large SMADES' autonomous desalination solar-driven membrane distillation plant in Aqaba, Jordan. Desalination 2007;217(1–3):17–28.
[101] Banat F, Jwaied N. Economic evaluation of desalination by small-scale autonomous solar-powered membrane distillation units. Desalination 2008;220(1–3):566–73.
[102] Hogan PA, et al. Desalination by solar heated membrane distillation. Desalination 1991;81(1–3):81–90.
[103] Bier C, Plantikow U. Solar-powered desalination by Membrane Distillation (MD). Presented at the IDA World Congress on desalination and water sciences. Abu Dhabi; 1995.
[104] Fath HES, et al. PV and thermally driven small-scale, stand-alone solar desalination systems with very low maintenance needs. Desalination 2008;225(1–3):58–69.
[105] Ohta K, et al. Experiments on sea water desalination by membrane distillation. Desalination 1990;78(2):177–85.
[106] Walton JC, U. of T. at E. P. C. of Engineering, E.R. T. (US) W. T. Engineering, and R. Group, Solar and waste heat desalination by membrane distillation. US Dept. of the Interior, Bureau of Reclamation, Denver Office, Technical Service Center, Environmental Services Division, Water Treatment Engineering and Research Group, 2004.
[107] Banat F, Jwaied N, Rommel M, Koschikowski J, Wieghaus M. Desalination by a 'compact SMADES' autonomous solar powered membrane distillation unit. Desalination 2007;217(1–3):29–37.
[108] Al Madani HMN. Water desalination by solar powered electrodialysis process. Renewable Energy 2003;28(12):1915–24.
[109] Reahl ER. Half a century of desalination with electrodialysis. GE Water & Process Technologies, General Electric Company; 2006.
[110] Ortiz JM, Expósito E, Gallud F, García-García V, Montiel V, Aldaz A. Electrodialysis of brackish water powered by photovoltaic energy without batteries: direct connection behaviour. Desalination 2007;208(1–3): 89–100.
[111] Kuroda O, et al. An electrodialysis sea water desalination system powered by photovoltaic cells. Desalination 1987;65:161–9.
[112] Adiga MR, Adhikary SK, Narayanan PK, Harkare WP, Gomkale SD, Govindan KP. Performance analysis of photovoltaic electrodialysis desalination plant at Tanote in Thar desert. Desalination 1987;67:59–66.
[113] Ishimaru N. Solar photovoltaic desalination of brackish water in remote areas by electrodialysis. Desalination 1994;98(1–3):485–93.
[114] Lichtwadt MA, Remmers HE. Water Treatment using solar-powered electrodialysis reversal. In: Mediterranean Conference on Renewable Energy Sources for Water Production. 1996.
[115] Photovoltaic electrodialysis system for brackish water desalination. University of Alicante; 2006.
[116] Madani AA. Zero-discharge direct-contact freezing/solar evaporator desalination complex. Desalination 1992;85(2):179–95.
[117] El-Nashar AM. Solar desalination using the vacuum freezing ejector absorption (VFEA) process. Desalination 1984;49(3):293–319.
[118] Khoshaim BH. 200 m^3/day solar sea water desalination pilot plant. Solar & Wind Technology 1985;2(3–4):173–82.